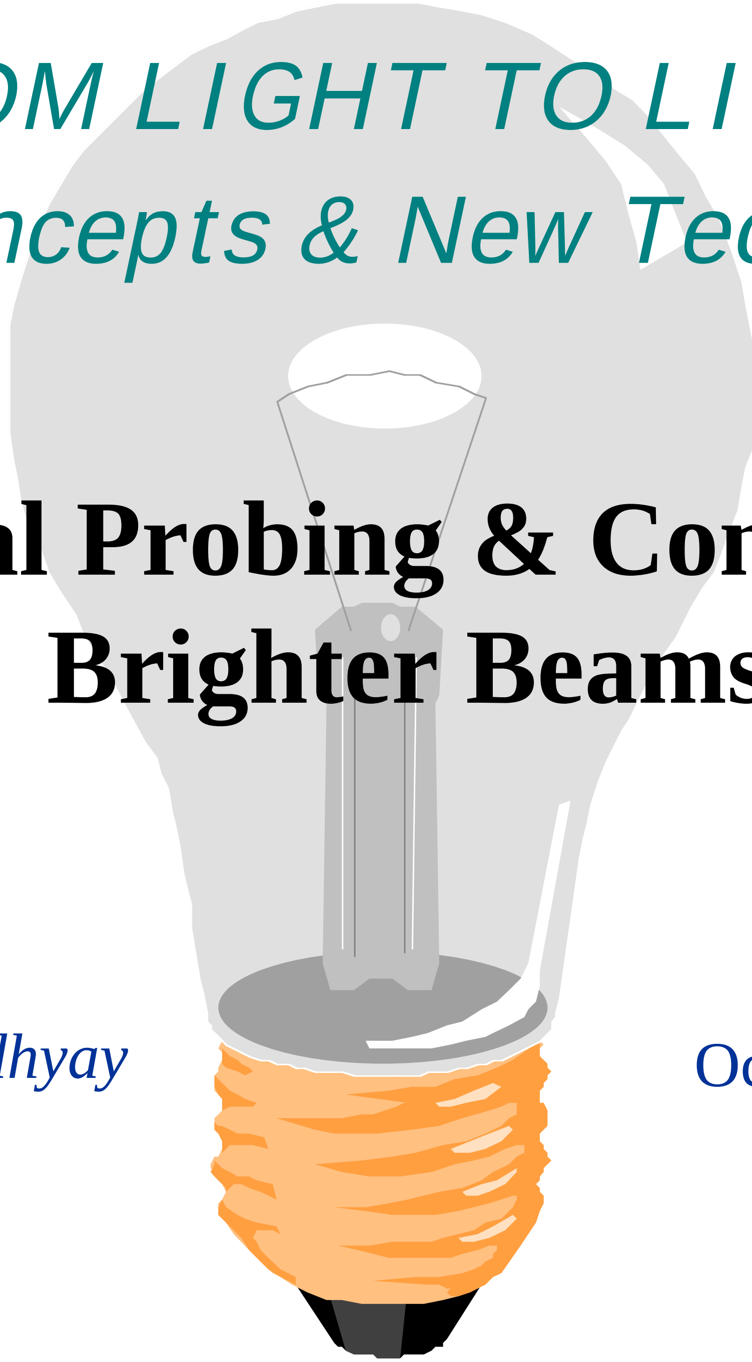


FROM LIGHT TO LIGHT :

New Concepts & New Technologies

Optical Probing & Control for Brighter Beams

Presented by

Swapan Chattopadhyay

ALS

October 3, 2000

Outline

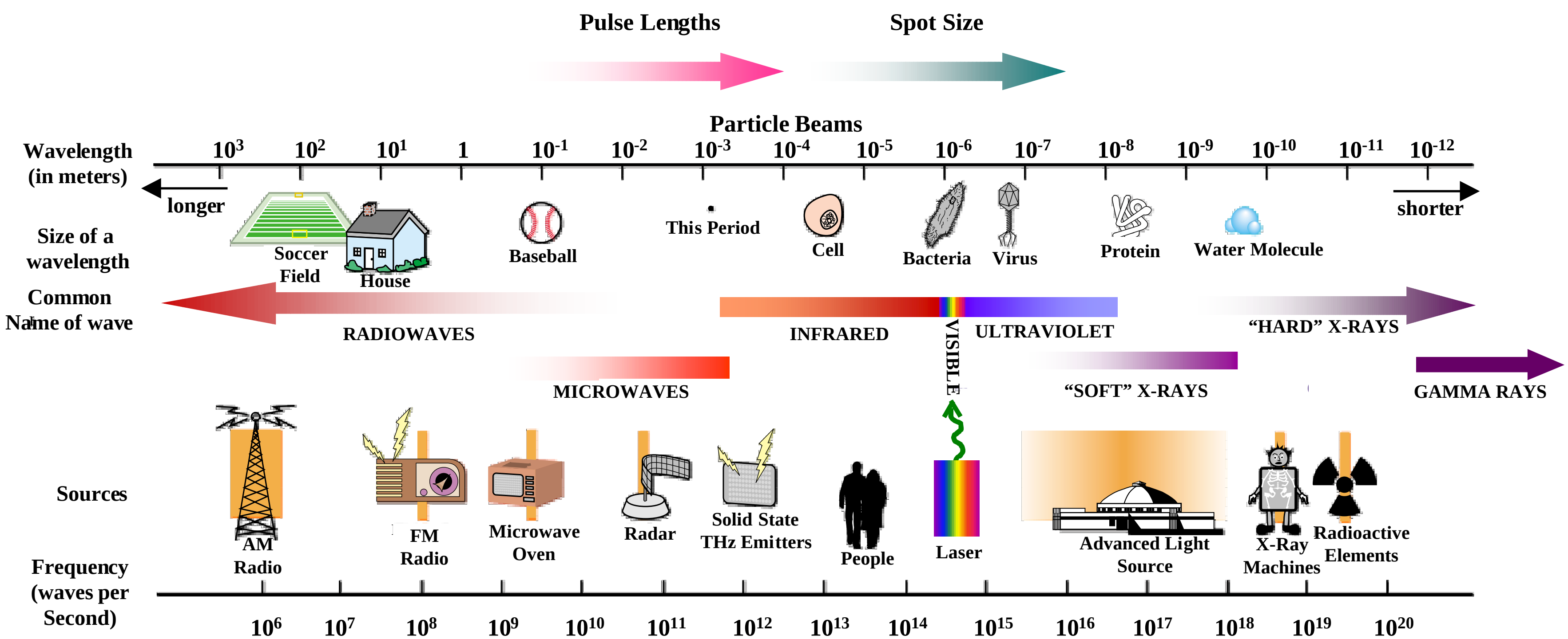
- Motivation for control at optical scale
- An example of optical slicing
- Applications of optical probing & control
  - attosecond slicing
  - pondermotive bunching
  - laser wakefield
  - femto-ring
  - optical stochastic cooling (OSC)
- Fundamental issues

Ideas being developed at the *Center for Beam Physics* with contributions from :

- Swapan Chattopadhyay
- John Corlett
- Eric Esarey
- Wim Leemans
- Kem Robinson
- Sasha Zholents
- Max Zolotorev

Particle Accelerators to date have taken full advantage of the microwave part of

THE ELECTROMAGNETIC SPECTRUM



Optical Manipulation of Particle Beams

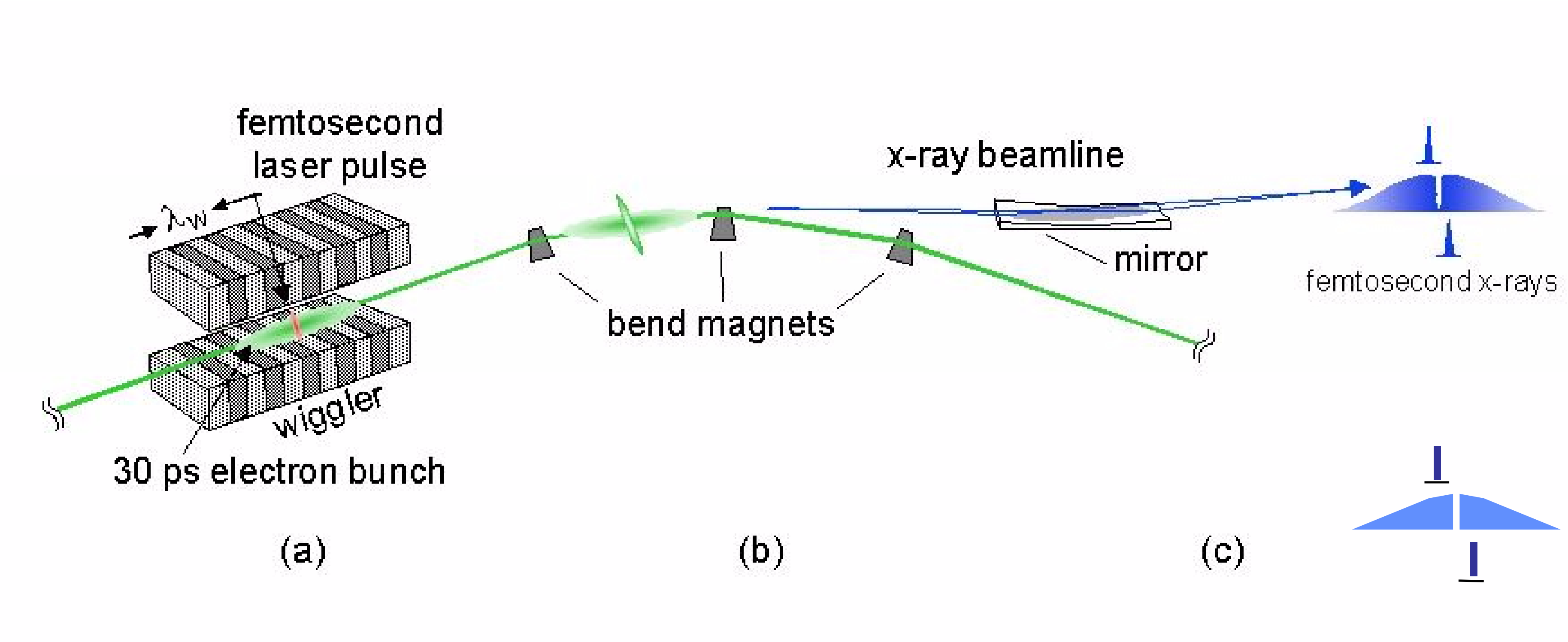
Today we can complement the GHz microwave rf technology by state-of-the-art short pulse high power compact lasers as work horses for particle accelerators.

However, just as in today's microwave technology involving beam manipulation over fractions of mms in time-scales of picoseconds at frequencies of GHz, one would have to learn to manipulate and control signals and particles at optical wavelengths of microns, in time-scales of femtoseconds and at frequencies of THz and higher in order to take advantage of today's optical technology.

The development of femtosecond kickers, choppers, bunch rotators etc., and THz manipulation of beams will be one of the most challenging jobs for future beam applications.

We are encouraged by our recently successful experimental experience.

Laser Femto-slicing of Electron Beams



Reference:
Generation of Femtosecond Pulses of Synchrotron Radiation
R. Schoenlein, S. Chattopadhyay, H.H.W. Chong, T.E. Glover, P.A. Heimann, C.V. Shank, A.A. Zholents, M.S. Zolotorev
Science, Vol. 287, No. 5461, March 24, 2000, p. 2237.

→ **Unique experiment in the world.**

→ **Optical Manipulation of Beams**

Applications of Optical Control

- Beam slicing
- Femto-second and atto-second control
  (10^{-15} s) (10^{-18} s)
- Optical diagnostics of beam granularity in phase space
- Luminosity control
- Optical stochastic cooling of phase space:

Unstable particles : Muons for neutrino sources & muon collider

Hadrons : for very large hadron collider

Attosecond Electron Bunches

for coherent ionization and excitation of atoms

Attosecond Pulses

10^{-18} seconds $\lesssim \tau \lesssim 10^{-15}$ seconds

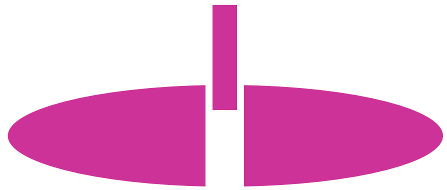
Femtosecond Laser → *Attosecond Electron Beam Pulse* → *Attosecond Light and X-rays*

allows pump-probe experiments @ 10^{-17} second scale

- Novel interactions of attosecond pulses with atoms/molecules/bulk matter
    - Exotic and complex excitation of atoms into "quantum entangled states"
    - Coherent Ionization of Atom
- Temporally coherent attosecond hard x-rays (10 keV) via Self Amplification of Spontaneous Emission (SASE)

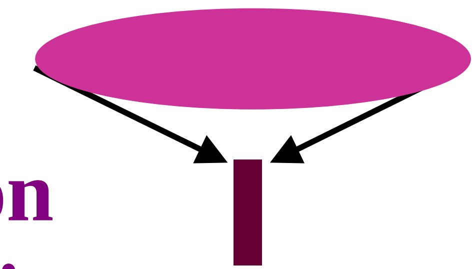
Techniques and Applications

Atto-slicing:



- Possibilities with ALS or a stand-alone linac with reasonable effort + $

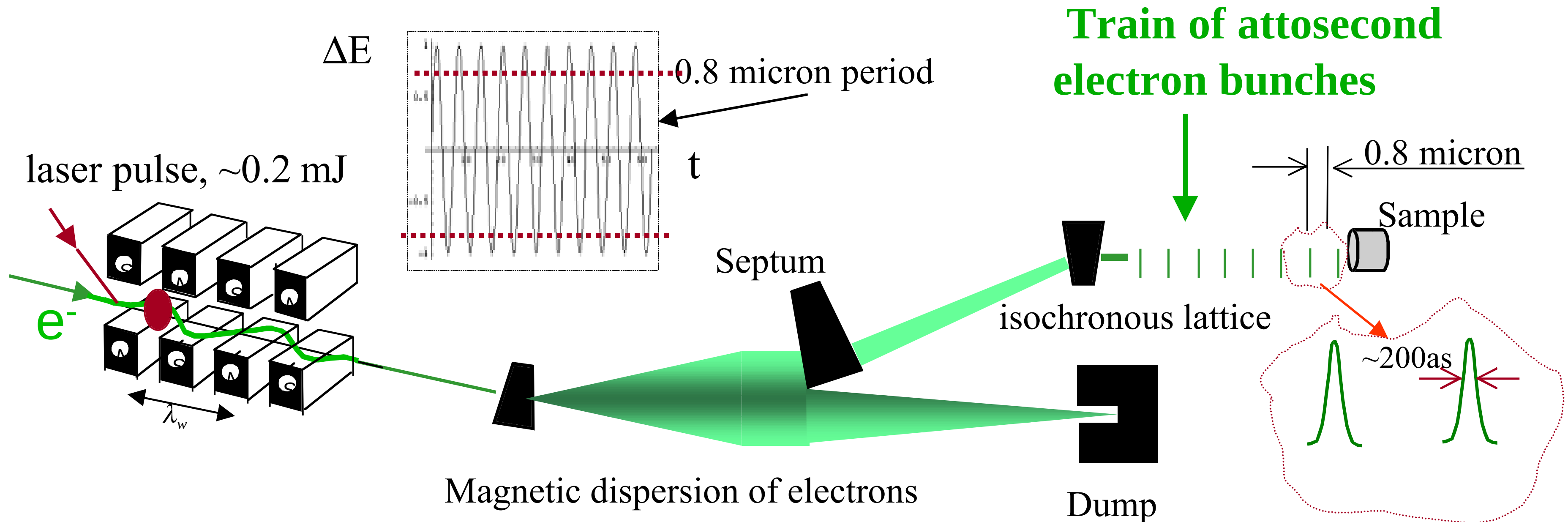
Atto-bunching:



- Laser-plasma acceleration
- Ponderomotive acceleration

Laser-assisted SASE FEL → **Forefront application**

Atto-Slicing: Laser Slicing Technique



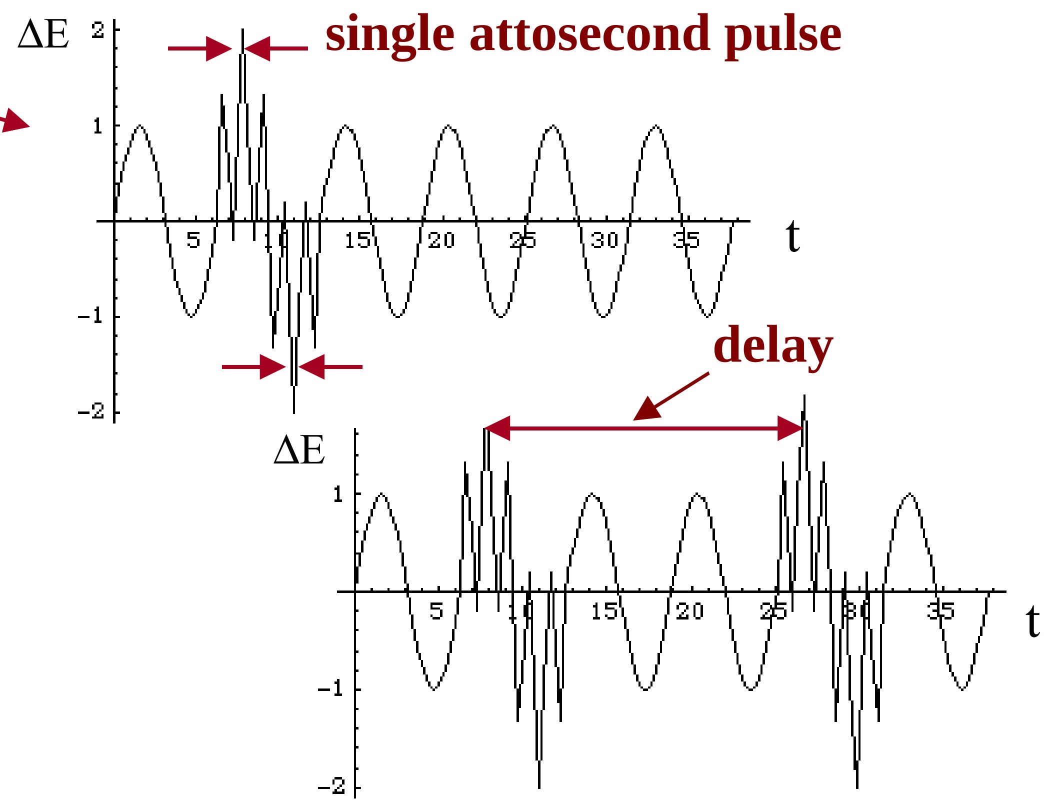
Flux of the attosecond electron bunches:
train of ~100 bunches, ~10^6 e/bunch, 10 kHz rep. rate

- **Energy modulation was demonstrated at the ALS for femtosecond x-ray generation**
- **Micro-bunching at 10 μm was demonstrated at ATF/BNL**
- **Electron pulse separation (slicing) down to 0.1 μm must be studied**

Laser Slicing Technique (cont'd)

One can also obtain:

- Two micro-bunch trains using top and bottom peaks of the energy modulation
- Single attosecond electron bunch by combining the energy modulation from two lasers



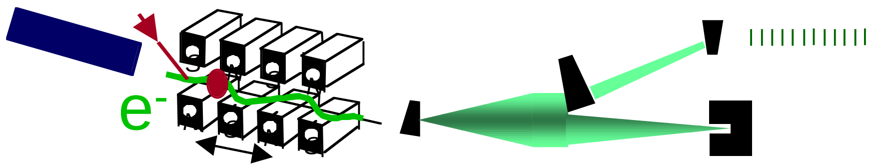
- Pulses with variable delay using top and bottom peaks

- Pulses with a given delay

Laser Slicing Technique (cont'd)

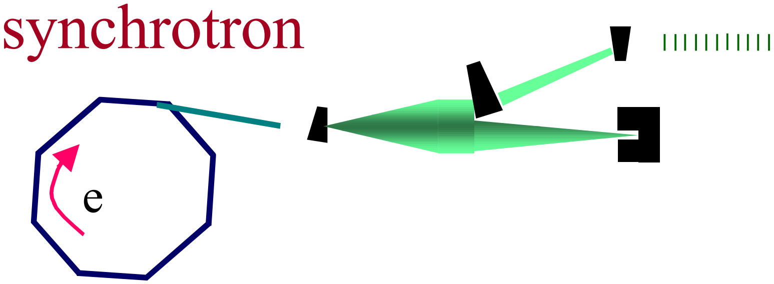
Source of electrons:

1) SC rf linac:
~100 MeV , 10 nC,
5 mm-mrad, 10kHz



(higher average flux, shorter pulses)

2) Synchrotron (ALS?):
~1500 MeV , 300x1nC,
5 mm-mrad, 1 kHz,
continues injection



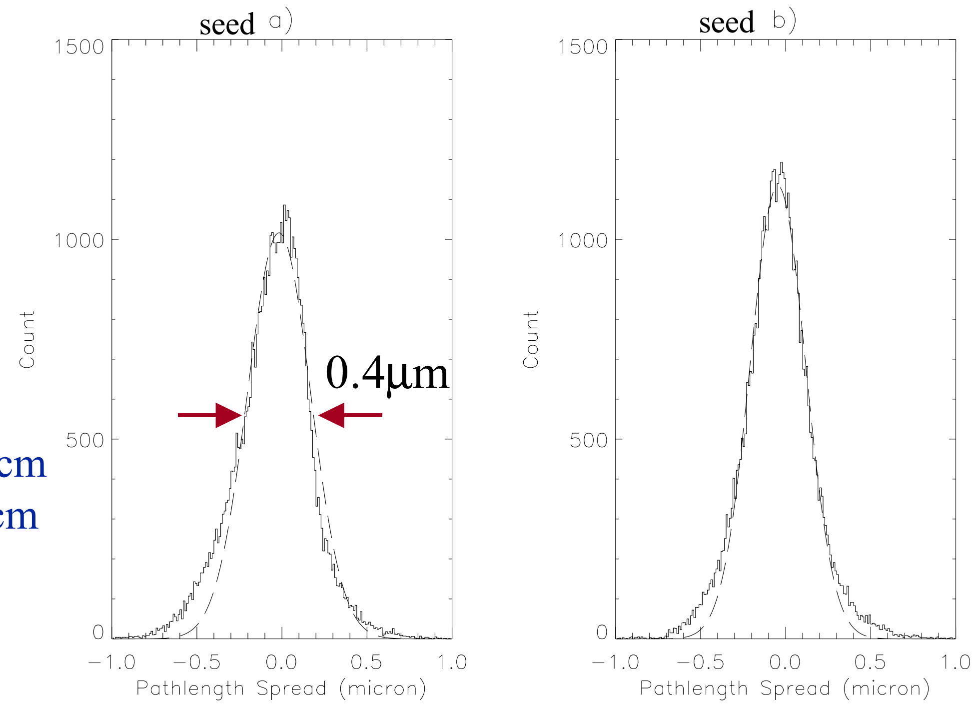
(better transverse emittance)

Laser Slicing Technique (cont'd)

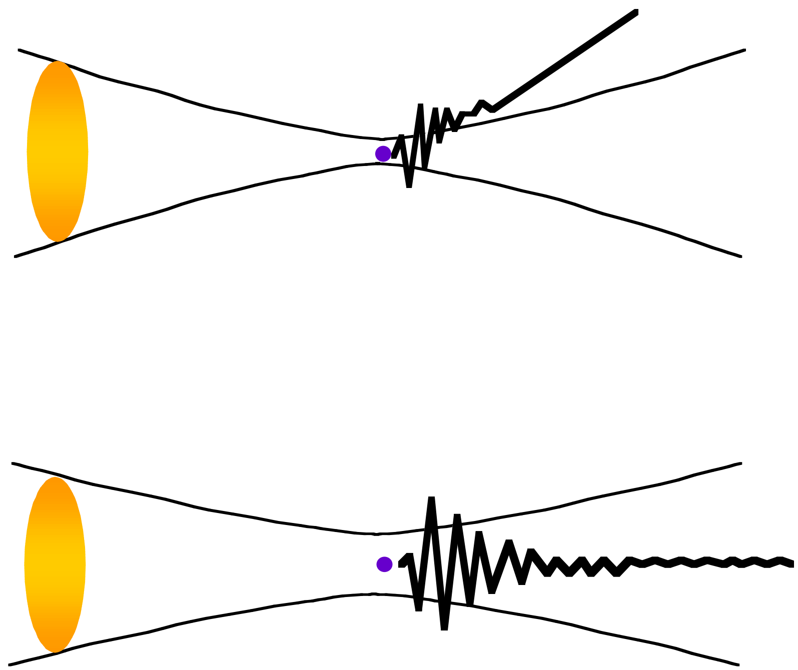
Test of isochronicity

Errors:

Quadrupole gradient : $\Delta G/G=1x10^{-3}$
Bending field: $\Delta B/B=1x10^{-3}$
Sextupole gradient: $\Delta S/S=1x10^{-3}$
Tilt angle: 0.2 mrad
Misalignment: 150 µm
Multipoles: $\Delta G/G=1x10^{-4}$ at r=3cm
$\Delta B/B=1x10^{-4}$ at r=3cm
Power supply ripple: $1x10^{-4}$



Acceleration and Scattering in Intense Laser Field



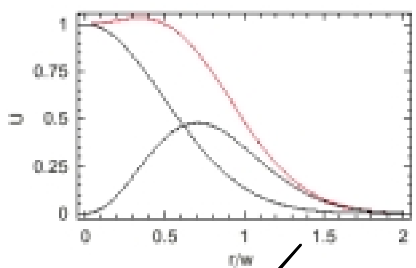
To obtain a high-brightness beam, we want to avoid Scattering during acceleration

Atto-Bunching: Dynamics of Ponderomotive Laser Acceleration

Laser provides acceleration, focusing and bunching

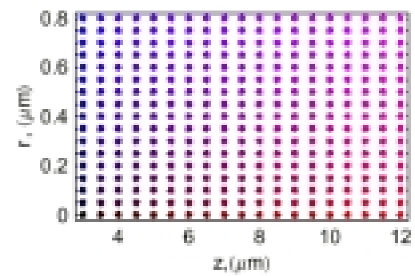
Laser mode

Intensity vs r

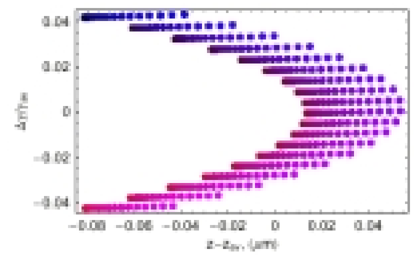


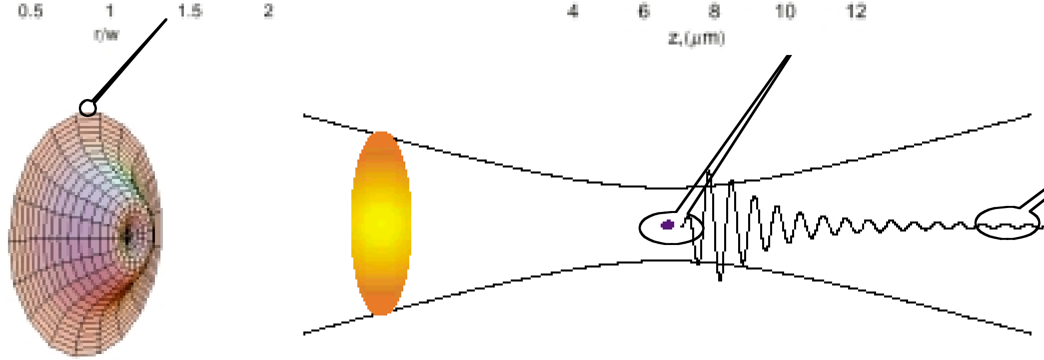
Evolution of longitudinal phase space

Initial (r,z)

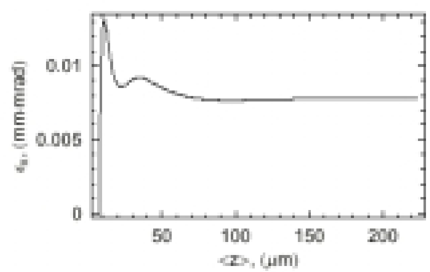


Final (γ,z)

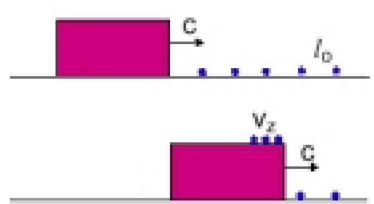




Emittance vs z



Attosecond bunching

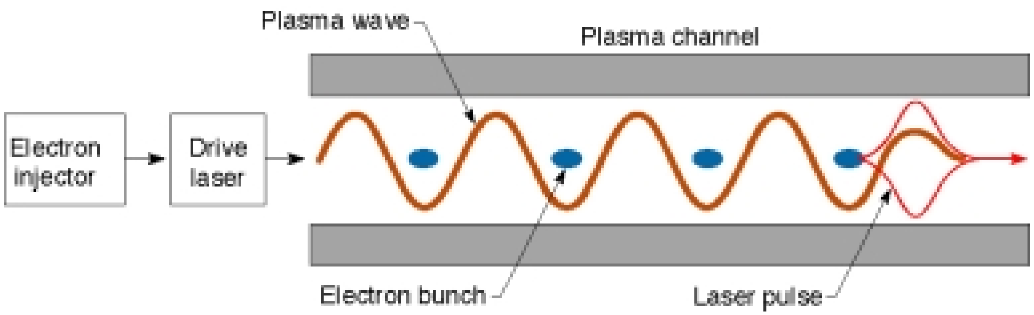


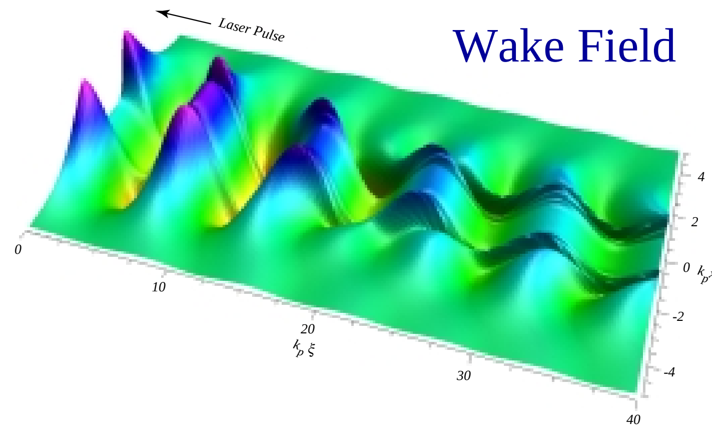
$$l_1 = l_0 \frac{c - v_z}{c} \approx l_0 \frac{1}{2\gamma^2}$$

Evolution of transverse phase space

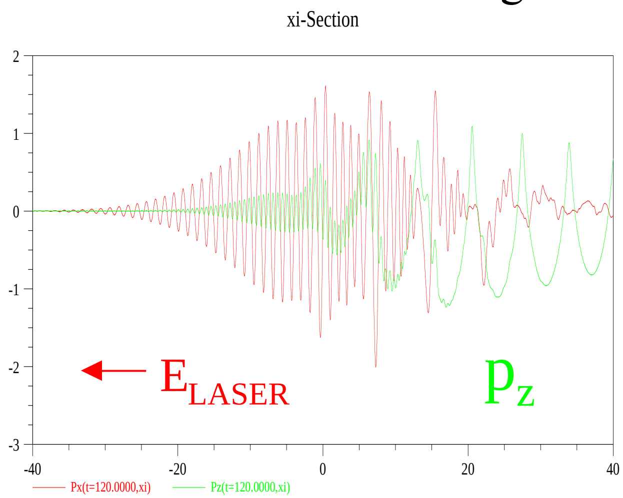
Atto-Bunching: Laser Wake Field Accelerators

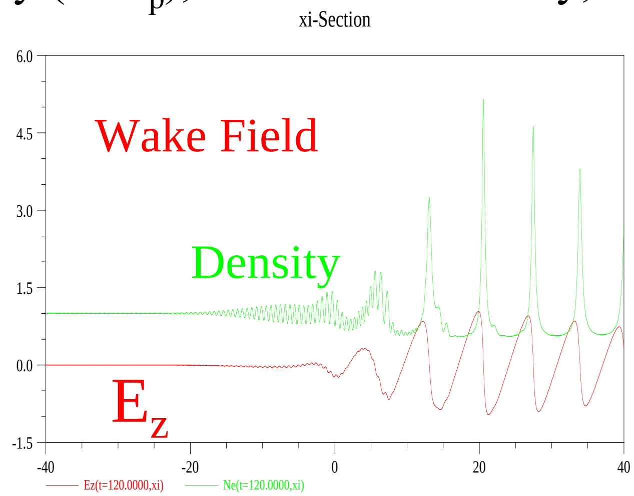
Standard LWFA: Resonant density ($L=\lambda_p$), controlled wake, externally injected electrons





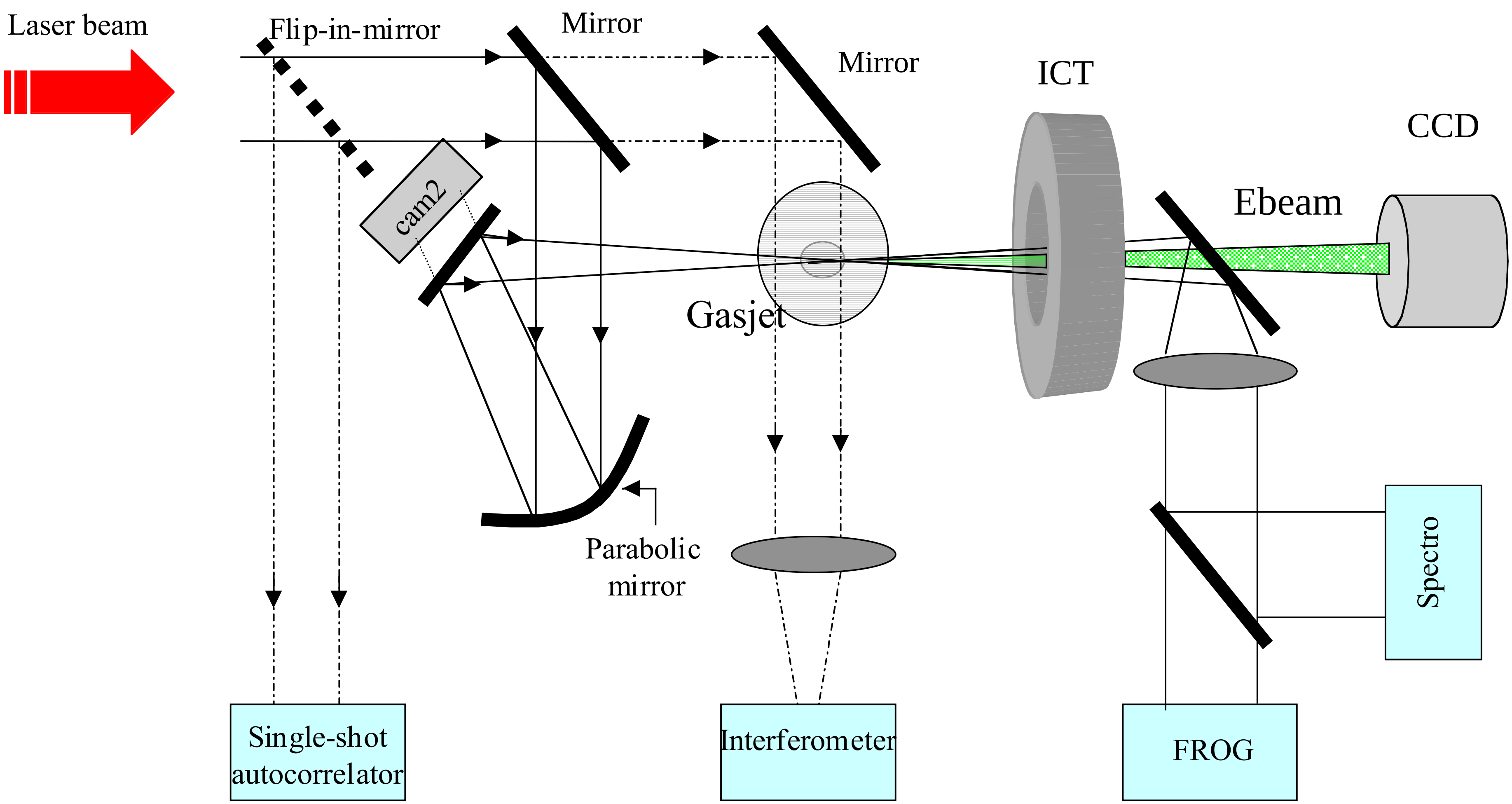
Self-Modulated LWFA: High density ($L>\lambda_p$), wake via instability, self-trapped electrons





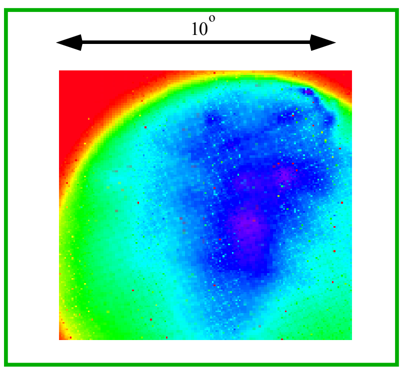
fs microbunches
> 1 nC
100% energy spread

Experimental Set Up: Optical Diagnostics



High Energy E-Beam Observed using Self-Modulated LWFA

Electron Beam Images



Neutron & Electron Yield vs. pulse duration

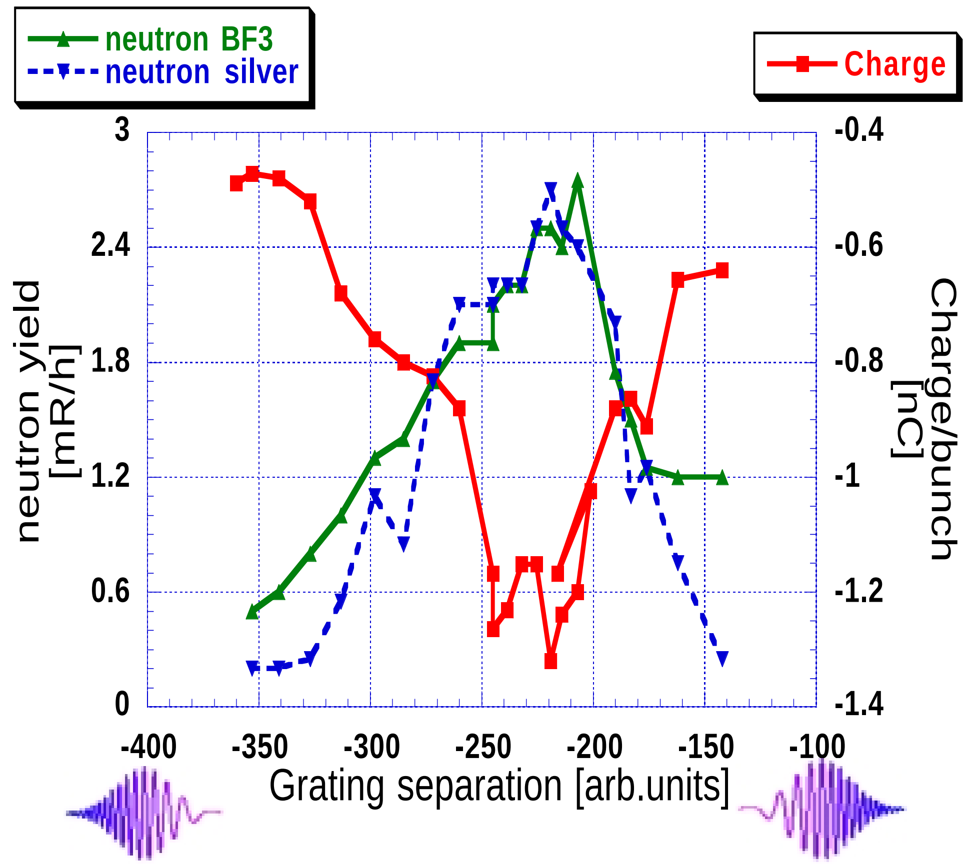


Table-Top Coherent SASE X-Ray FEL using a Laser Wiggler

FEL X-ray wavelength

$$\lambda_x = \frac{\lambda_w}{4\gamma^2}(1 + a^2)$$

Inverse gain length

$$\frac{1}{2\pi M_g} \approx \frac{1}{1+\varepsilon_b / \varepsilon_x} \sqrt{\frac{1}{2\gamma} \frac{I}{I_A} \frac{a^2}{1+a^2}}$$

Electron beam parameters

$N_e = 10^6$, $c\tau_e = 10^{-6}$ cm, $\varepsilon_{nb} = 10^{-6}$ cm rad

Transverse coherence requirement

$\varepsilon_b / \varepsilon_x < 10$

Examples

SASE E_x=10 keV

THz source (λ_w=100 μm)
γ = 500 (250 MeV)
E_w=20 J
$N_X = 6\text{x}10^8$

SASE E_x=10 keV

CO_2 laser (λ_w=10 μm)
γ = 160 (80 MeV)
E_w=4 J
$N_X = 2\text{x}10^8$

SASE E_x=1 keV

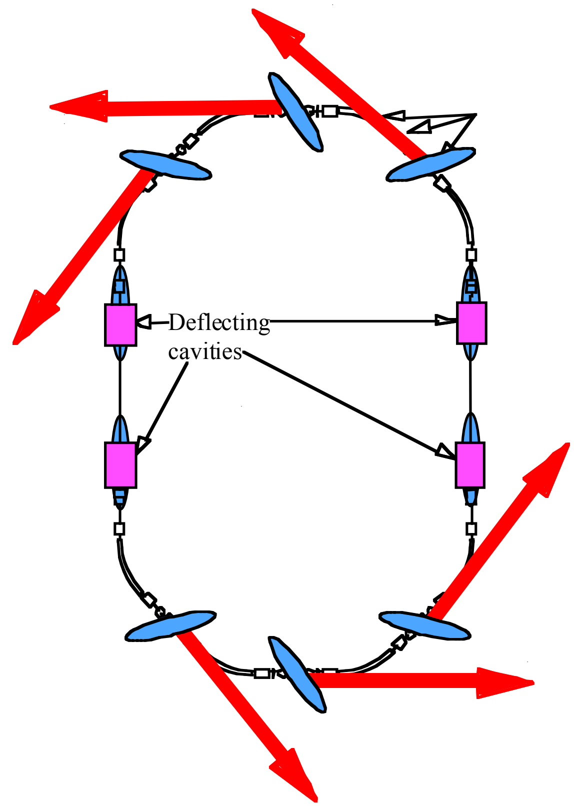
Ti laser (λ_w= 0.8 μm)
γ = 13 (6.5 MeV)
E_w=30 mJ
$N_X = 2\text{x}10^8$

Dedicated Permanent magnet Synchrotron Light Source for Ultra-fast X-ray Science

Berkeley Lab proposal for novel next generation synchrotron light source

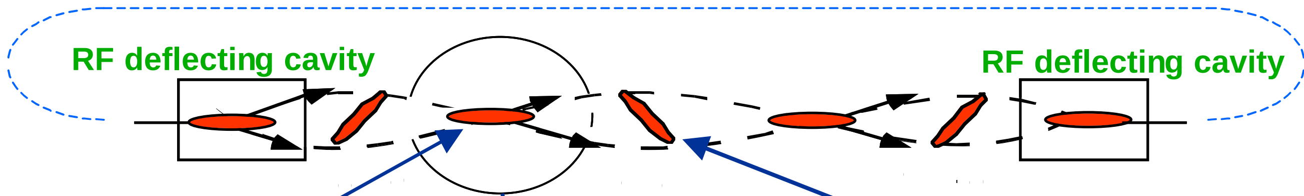
- **Dedicated facility for ultra-fast X-ray science**
  - **—Short pulse duration (~ 100 fs)**
  - **—Large flux (≈ ALS)**
  - **—High brightness (≈ ALS)**
  - ***—Large, multi-user facility***
  - ***—Improvement over existing facilities***
- **Fundamental time scales**
  - **Vibrational period of atoms**
    - – Fast phase transitions
    - – Kinetic pathways of chemical reactions
    - – Biological processes

—Regime largely unexplored



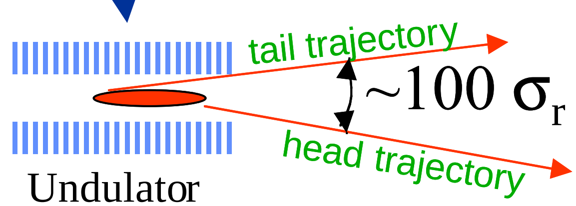
Lattice concept

RF-deflection - a Novel AFRD Idea to Rotate Bunches in a Synchrotron Light Source



$$\delta y'(z) = \frac{eU}{E_{beam}} \sqrt{\frac{\beta_{cavity}}{\beta_{ring}}} \sin(k_{rf} z)$$

$$\delta y(z) = \frac{eU}{E_{beam}} \sqrt{\beta_{cavity}\beta_{ring}} \sin(k_{rf} z)$$



Take into account:

— Electron beam: size & divergence

— Radiation: diffraction limited size & opening angle

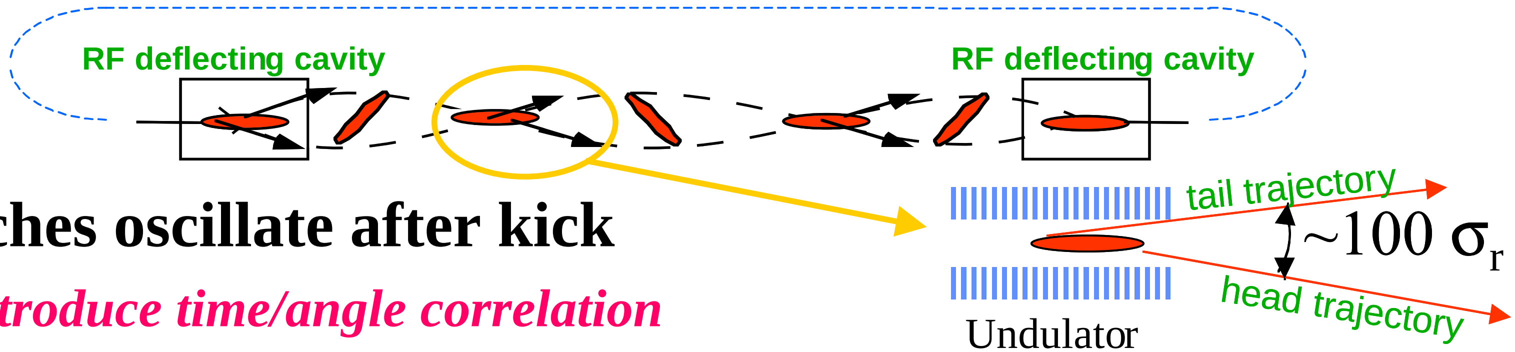
$$\frac{eU}{beam} \geq \frac{M}{k_{rf}\sigma_z} \frac{\sqrt{\varepsilon_y}}{\beta_{rf}} \sqrt{1 + \left(\frac{\sigma_{r'}}{\sigma_{y'}}\right)^2}$$

$$\frac{eU}{beam} \geq \frac{M}{k_{rf}\sigma_z} \frac{\sqrt{\varepsilon_y}}{\beta_{rf}} \sqrt{1 + \left(\frac{\sigma_{r}}{\sigma_{y}}\right)^2}$$

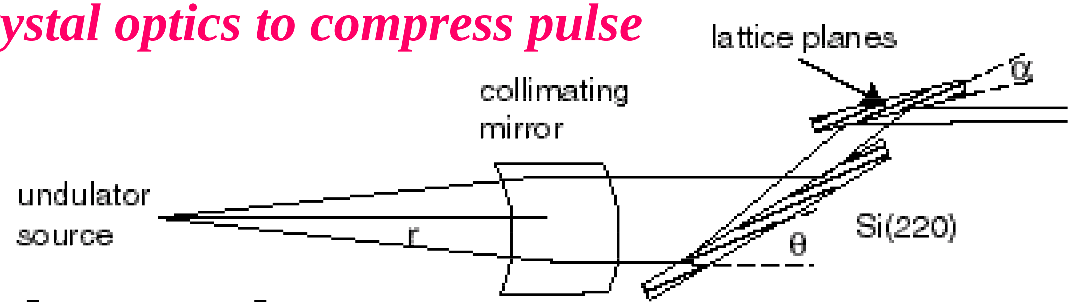
U is the cavity voltage, M is the number of resolvable sub-picosecond "slices", $\sigma_{r'}$ is the radiation opening angle, $\sigma_{y'}$ is the electron beam divergence

RF-deflection - a novel AFRD idea to rotate bunches in a synchrotron light source

- **RF cavities operating in TM_{110} mode "rotate" electron bunches**
  - **—Linear deflection of particles along bunch**
  - **—Head and tail of electron bunches receive opposite kicks**



  - **—Bunches oscillate after kick**
    - ***Introduce time/angle correlation***
  - **—~ 100 fs effective bunch length at radiation source point**
    - ***Use asymmetrically cut crystal optics to compress pulse***

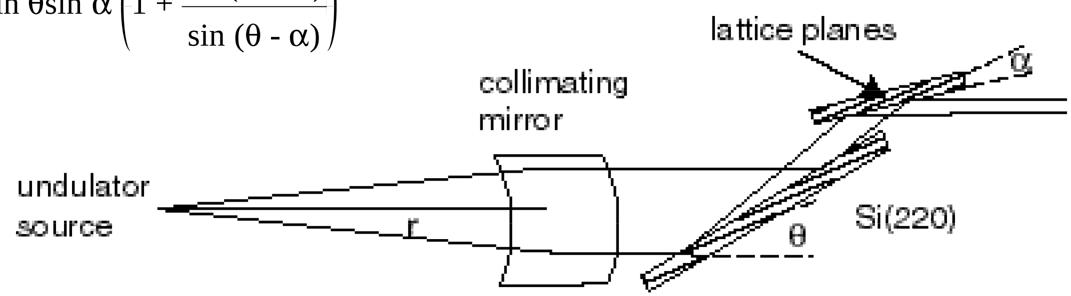


- **Serve many beamlines simultaneously**

A multi-user facility

- **This technique can serve many beamlines simultaneously with a single set of the RF "crab" cavities**
- **Femtosecond pulses are obtained from all electron bunches**
- **x-ray pulse compression to ~100 fs using asymmetrically cut crystal**

$$\delta l \approx 2\frac{r\ \delta y'}{\sin(\theta - \alpha)} \sin\theta \sin\alpha \left(1 + \frac{\sin(\theta + \alpha)}{\sin(\theta - \alpha)}\right)$$

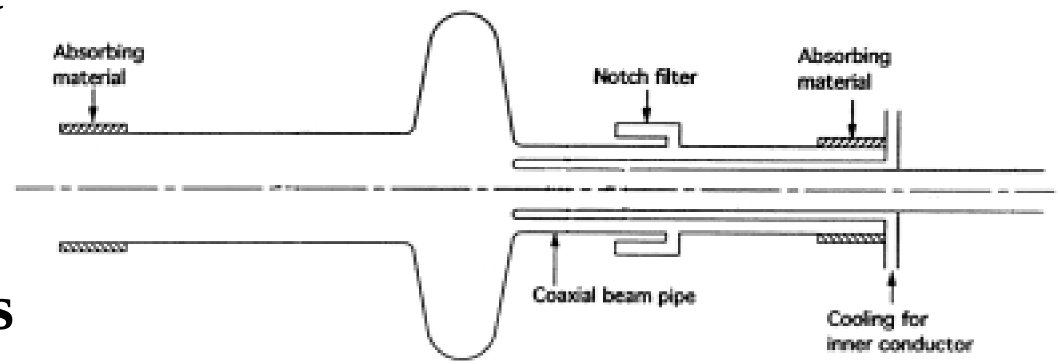


- **Flux of the femtosecond x-rays utilized in a pump-probe experiment is limited by the repetition rate of the pump laser pulse**
  - **2 - 20 mJ of energy (50 mJ cm^{-2})**
  - **500 kHz for 1W laser**

Deflecting cavities - a critical technology

- $\mathbf{TM_{110}}$ **mode**
  - —**Introduces angular kick along individual bunches**
  - —**1 GHz, 1.5 - 2.5 MV**
  - —**Superconducting cavity**
    - **Deformed "bell" shape**

$$y'(z) = \frac{eU}{E_{beam}} \sin(k_{rf} z) \qquad \frac{eU}{\text{beam}} \geq \frac{M}{k_{rf}\sigma_z} \frac{\sqrt{\varepsilon_y}}{\beta_{rf}} \sqrt{1 + \left(\frac{\sigma_{r'}}{\sigma_{y'}}\right)^2}$$

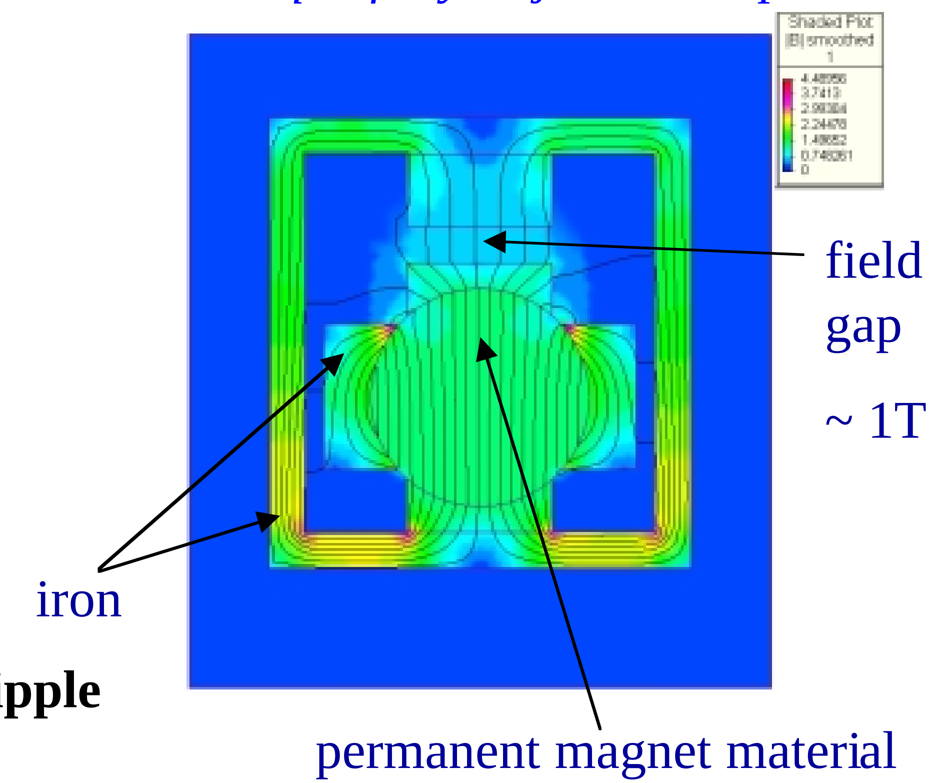


- **Damp other cavity modes**
  - **Higher and lower frequencies**
    - – ~ kW HOM power
- **Phase stability**
  - —**Cancel oscillation at second RF cavity**

Low-torque variable-field permanent magnet families

- **Recent design concepts by *Halbach* and *Robinson***
  - **Constant stored energy**
    - – *Simple, inexpensive hardware*

Zero-torque fully-adjustable dipole



- **Significant costs savings**
  - **—Reduced infrastructure**
    - **Cable plant**
    - **Power supplies**
    - **Air conditioning**
    - **Water coolant**
  - **—Improved stability**
    - **No thermal gradients**
    - **No influence of power supply ripple**

Pump-probe experiments

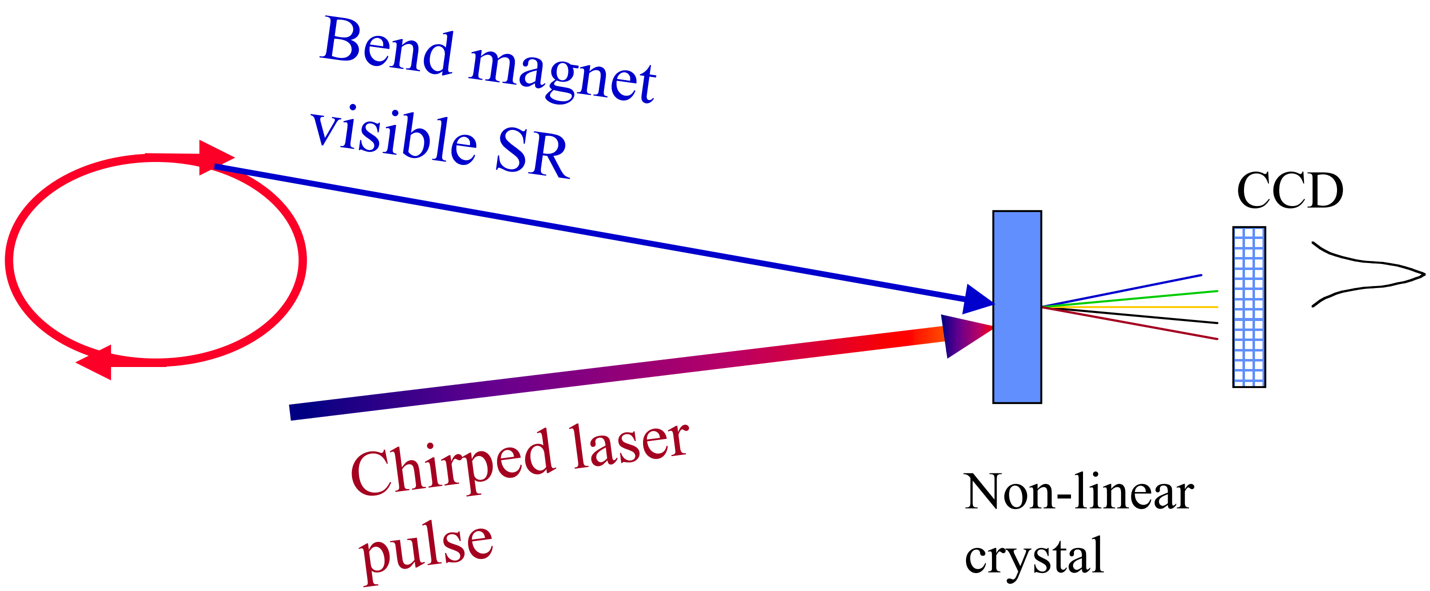
- **Flux of the femtosecond x-rays utilized in a pump-probe experiment is limited by the repetition rate of the pump laser pulse**
  - **2 - 20 mJ of energy (50 mJ cm^{-2})**
  - **500 kHz for 1W laser**
    - Shutter may be used to reduce flux on sample
- **~ 1 ps laser jitter relative to the master clock**
- **Measure the time of a signal relative to the laser pulse**
- **Feedback locks system**

—50 fs jitter

  - *Kiewiet et al, Proc. EPAC 2000, Vienna, 2000*

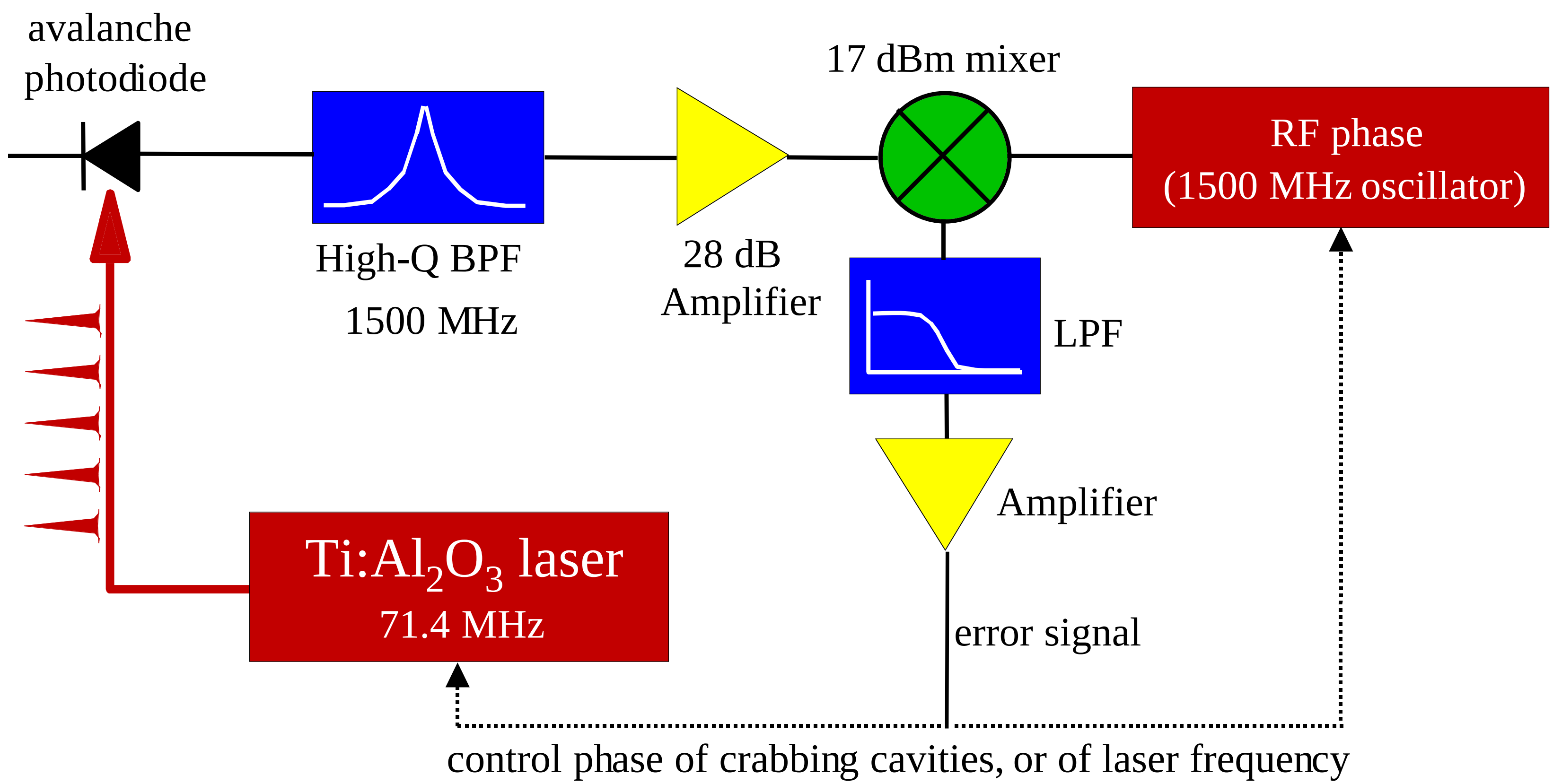
Measure the Relative Time between Laser and Synchrotron Radiation

- **Jitter of the laser relative the electron bunch can be measured to dt ~ (10 - 100) fs**



- **10^7-10^8 visible photons are required in a single shot**

RF Locking with <100 fs Timing Jitter



$\Delta t \sim 100$ fs $\longrightarrow$ $\Delta t/T \sim 2\text{x}10^{-4}$ (1500 MHz)

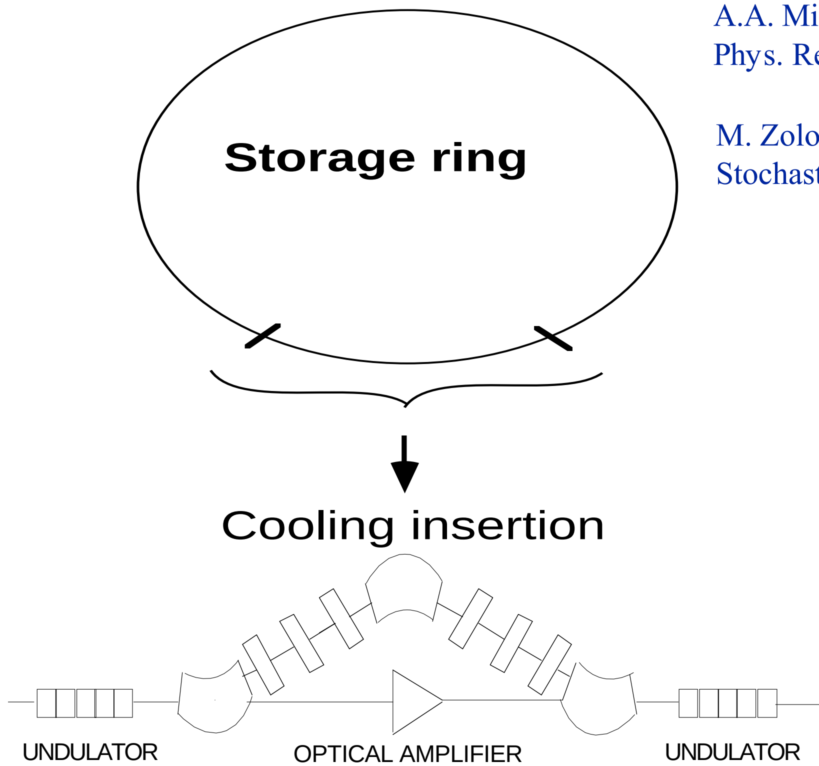
50 fs jitter demonstrated

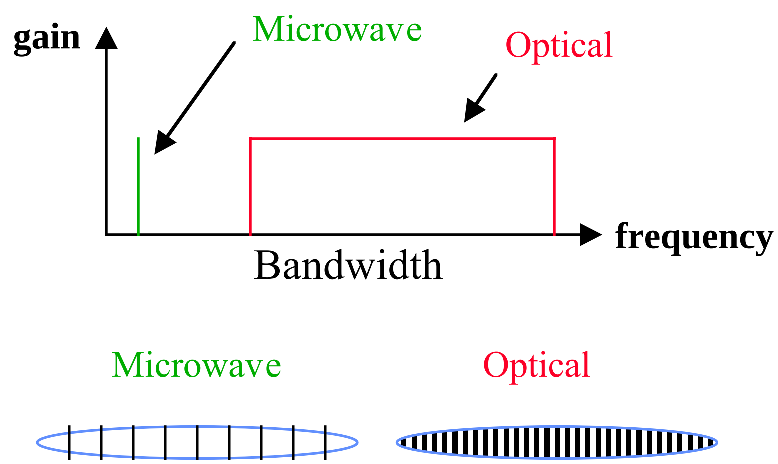
(Kiewiet et al, EPAC 2000, Vienna, 2000)

Optical Stochastic Cooling

A.A. Mikhailichenko and M.S. Zolotorev, "*Optical stochastic cooling*", Phys. Rev. Lett. , Vol. .71, N25, (1993), p. 4146.

M. Zolotorev and A. Zholents, "Transit-time Method of Optical Stochastic Cooling", Phys. Rev. E, Vol. 50, No. 4, (1994), p. 3087.





OSC uses optical amplifier and undulators as a pick-up and a kicker.

The amplifier bandwidth is $\sim 10^{13}$ Hz.

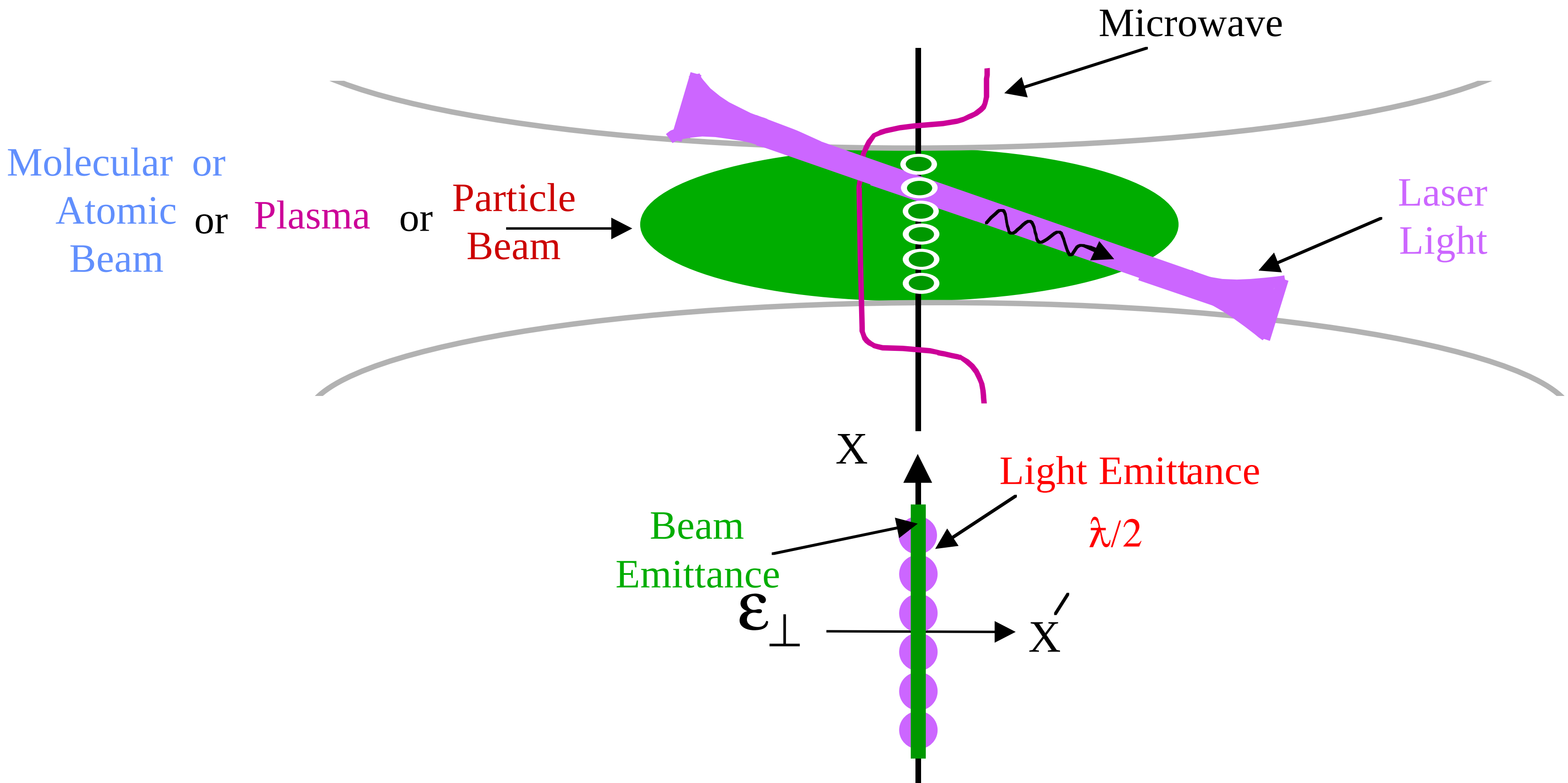
(Compare with $\sim 10^{9}$ Hz for microwave stochastic cooling)

Correspondingly, OSC has a potential for $\sim 10^{4}$ faster damping.

Particle Beam is fully Resolved in Space & Time by Light Beam

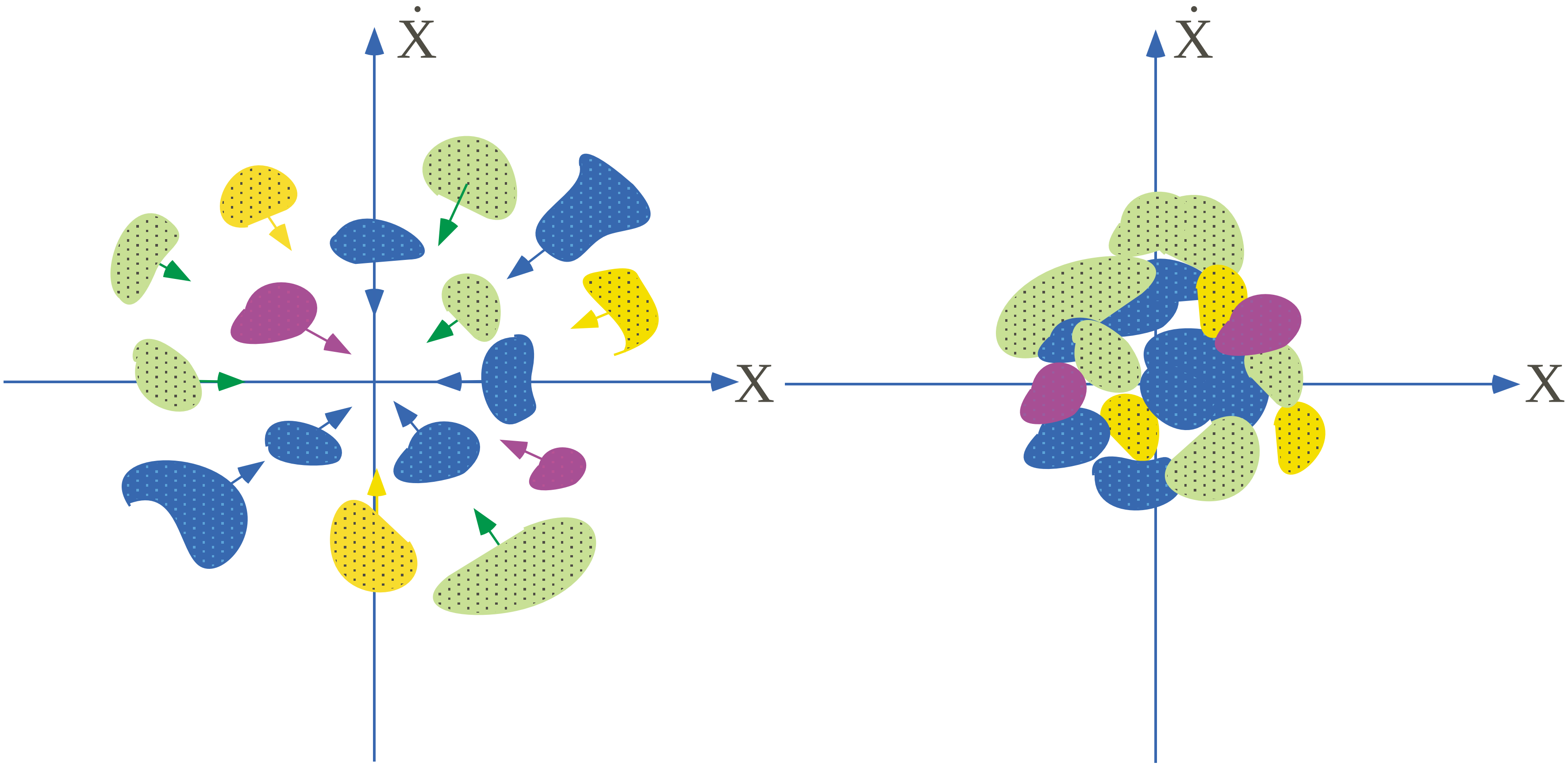
Cooling Rate $<\tau>^{-1}$ α Degree of Control in Phase Space α Number of Independent Phase Space Samples Probed $\equiv \frac{N}{N_s}$

Cooling Time $\propto N_s \equiv$ No. of Particles in a Sample



Coherence Volume of Light << Beam Emittance

Phase-Space Cooling in Any One Dimension



A Particular List of Parameters for a 2 TeV x 2 TeV Muon Collider Utilizing Optical Stochastic Cooling

	Units	This Study	CDR Ref.[8]
Beam energy	TeV	2	2
Circumference	km	8.08	8.08
Number of muons		4.5×10^{8}	2×10^{12}
Number of bunches of each sign		2	2
Beta-function at the IP	µm	10	3000
Bunch length	µm	10	3000
Peak current	kA	2	32
Transverse beam size at the IP	µm	1.3×10^{-3}	3
Beam divergence at the IP		1.3×10^{-4}	1×10^{-3}
Beam energy spread		1×10^{-3}	7×10^{-4}
Beam-beam parameter		0.15	0.045
Repetition rate	Hz	200	15
Luminosity	$Cm^{-2}s^{-1}$	1×10^{35}	1×10^{35}

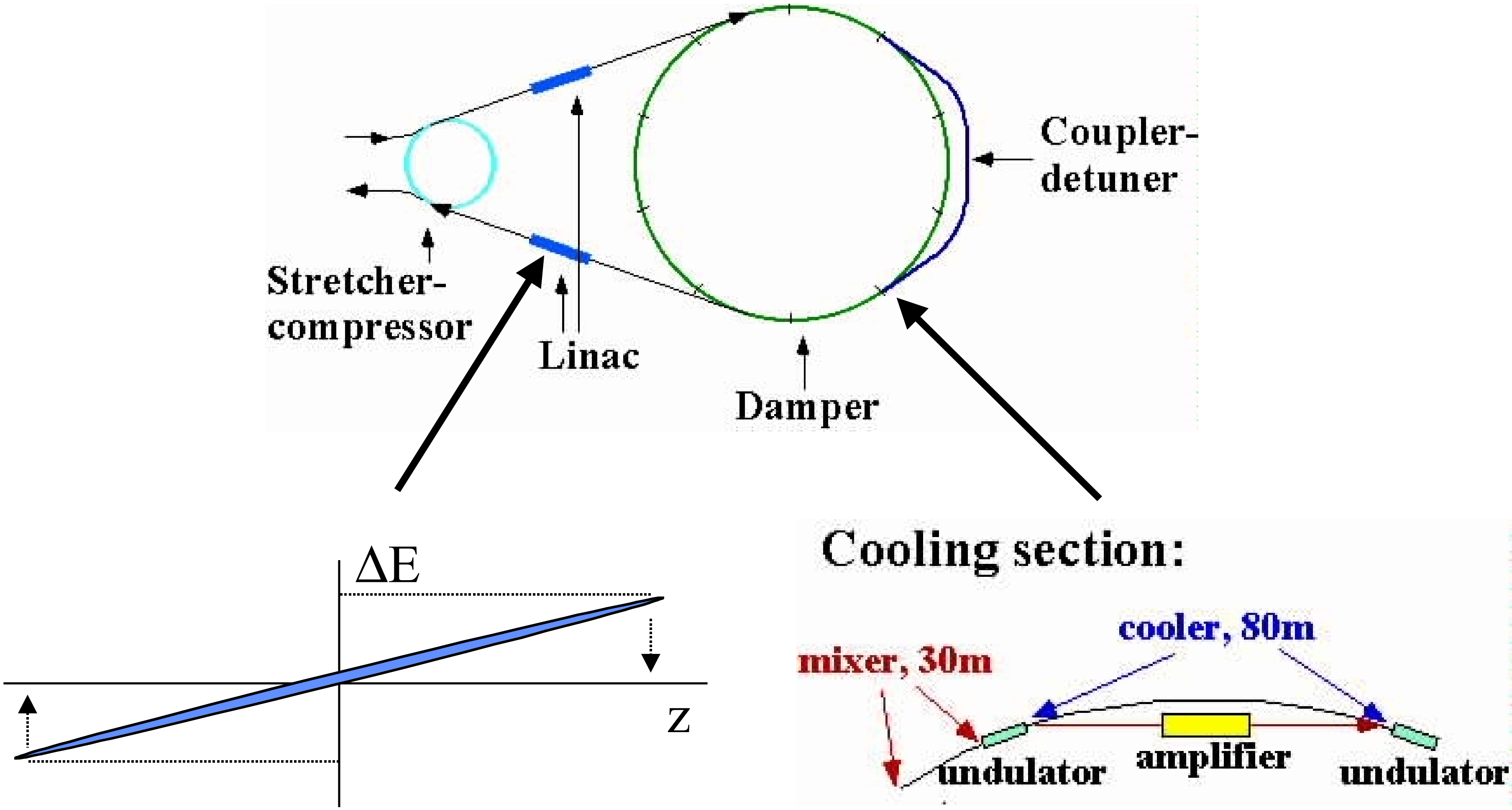
Parameters for Muon Cooling

	Units	Value
Beam energy	GeV	100
Repetition rate	Hz	200
Input beam characteristics		
Number of muons		3×10^{9}
Transverse emittance	cm-rad	2×10^{-3}
Longitudinal emittance, $\gamma\sigma_z\sigma_e$	cm	20
Beam energy spread, σ_e		1×10^{-3}
Bunch length, σ_z	cm	20
Stretcher-compressor		
Circumference	m	300
Momentum compaction		0.33
Induction linac		
Pulse duration	μs	1
Energy gain	MeV	± 125
Damping rings		
Circumference	m	1100
Number of rings		3
Number of injected muons		2×10^{9}
Beam energy spread, σ_e		2×10^{-6}

Parameters for Muon Cooling, *cont'd*

	Units	Value
Bunch length, σ_z	m	100
Number of sample particles		25
Longitudinal damping time	turns	75
Transverse damping time	turns	30
Undulator period	cm	50
Peak undulator field	T	10
Number of periods		14
Dispersion function	m	100
Beta function	m	2
Optical amplifier		
Number of amplifiers		10
Amplified light energy	J	1
Average output power	W	200
Amplitude gain		$3.8\text{x}10^4$
Wavelength	nm	800
Output beam characteristics		
Number of beams		$4.5\text{x}10^8$
Transverse emittance	cm-rad	$3\text{x}10^{-7}$
Longitudinal emittance	cm	$2\text{x}10^{-2}$
Cooling time	ms	4

A Scheme for Optical Stochastic Cooling of Muons



Fundamental Issues

We expect: $$< \tau >^{-1} \sim \frac{1}{[N_s]}$$ cooling time

But, in practice, there is always amplifier noise which modifies cooling rate to :

$$< \tau >^{-1} \sim \frac{1}{[N_s + N_n]}$$

where $N_n \equiv$ sample population that can generate a noise signal equivalent to the optical amplifier noise

→ → → → What is N_n ?

Fundamental Issues

Each particle emits 'α' photons per turn, where $\alpha \equiv$ fine structure constant ~ 1/137

Total no. of equivalent noise photons is ~ αN_n

Fundamental Issues

Theoretical minimum of optical amplifier noise is one noise photon per optical mode :

$$\alpha N_n \sim 1 \Rightarrow N_n = 1/\alpha$$

$$< \tau >^{-1} \simeq \frac{1}{[N_s + (1/\alpha)]}$$

Fundamental Issues

For large sample population, $N_s \sim 10^7 - 10^9$,
the number of equivalent
photons from sample and amplifier :

$$N_p = \alpha\, N_s + \alpha N_n \sim (10^5 - 10^7) + 1 >> 1.$$

This large no. of photons generate an electric field in the far-field regime which is describable as classical light

Large "degeneracy parameter": large number of photons in a coherence volume

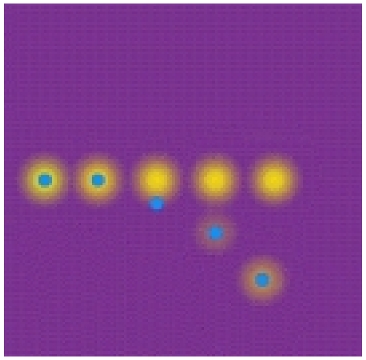
Fundamental Issues

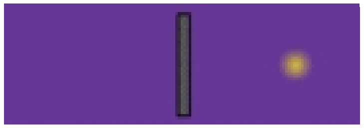
For small sample population, $N_s \sim 50 - 100$,
the number of equivalent
photons from sample and amplifier :
$N_p \sim (0.5 - 1) + 1 \sim O(1)$.
These few photons generate a field which
is intrinsically non -classical and quantum mechanical.

Small "degeneracy parameter": small number of photons in a coherence volume

How does stochastic cooling work in
this quantum limit ??

Radiation for Charged Particles—
A Simple Physical Vision





http://www.lbl.gov/educational sites/The World of Beams

Fundamental Issues

Understanding "Quantum Optics"
driven by
accelerated changes would
be critical
in these studies